The Impact of Footwear and Walking Distance on Gait Stability in Diabetic Patients with Peripheral Neuropathy

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Background: We explored gait differences in patients with diabetes and peripheral neuropathy (DPN) and aged-matched controls over short and long walking distances. The potential benefit of footwear for improving gait in patients with DPN was also explored.

Methods: Twelve patients with DPN and eight controls walked at their habitual speed over short (7 m) and long (20 m) distances under two conditions: barefoot and regular shoes. A validated system of body-worn sensors was used to extract spatiotemporal gait parameters. Neuropathy severity was quantified using vibratory perception threshold measured at the great toe.

Results: Gait deterioration in the DPN group was observed during all of the walking trials. However, the difference between patients with DPN and participants in the control group achieved statistical significance only during long walking distance trials. Shod and barefoot double support times were longer in the DPN group during long walking distances (>20%, P = .03). Gait unsteadiness, defined as coefficient of variation of gait velocity, was also significantly higher in the DPN group when barefoot walking over long distances (83%, P = .008). Furthermore, there was a high correlation between neuropathy severity and gait unsteadiness best demonstrated during the barefoot walking/long walking distance condition (r = 0.77, P < .001). The addition of footwear improved gait steadiness in the DPN group by 46% (P = .02). All differences were independent of age, sex, and body mass index (P ≤ .05).

Conclusions: This study suggests that gait alteration in patients with DPN is most pronounced while walking barefoot over longer distances and that footwear may improve gait steadiness in patients with DPN. (J Am Podiatr Med Assoc 103(3): 165-173, 2013)
protection, to decrease the risk of foot ulceration, and for the purposes of off-loading. The therapeutic effects of using shoes in these areas have been the topic of research for several decades. However, less is understood about the effects of footwear on standing and dynamic balance and fall risk.

Several recent studies have indicated that falls in older adults can, at least partly, be attributed to the use of popular footwear. Soft-soled shoes, for example, which are often used for improving comfort and reducing pain, may also dampen tactile input from the plantar surface of the foot. This, in turn, can alter somatosensory feedback, a key sensory feedback system needed for postural control. On the other hand, footwear has also been described as an important modifiable factor (eg, environmental) that can be used to minimize the risk of falling. Tactile and proprioceptive mechanisms can be enhanced by therapeutic shoes and their modifications, which may improve balance and subsequent risk of falling. Greater compression at the ankle may also act to improve balance by increasing feedback from cutaneous receptors in the foot and ankle, thereby improving joint position sense. In addition, wearing appropriate footwear with a suitable arch support has been found to reduce mediolateral motion of center of mass while walking and improve balance control. Therefore, the net effect of footwear on fall risk in older adults and other at-risk populations remains unclear.

Several studies have previously addressed gait alterations that occur in patients with diabetes. However, most of these studies explored walking in gait laboratories, which have inherent space restrictions; used targeting force plates, which have the limitation of capturing more than a step; or used a treadmill, which may regulate the speed, rhythm, and path of the individual’s walking. These laboratory conditions do not always replicate the natural environments in which patients are usually active. As a result, the impact of footwear on gait parameters measured outside of the gait laboratory has received little attention to date. Advances in the technology of body-worn sensors during the past decade have recently opened new avenues for exploration into gait assessment outside the confines of the gait laboratory.

In this study, we set out to investigate changes in gait parameters that patients with DPN may encounter during typical activities of daily living. To better mimic these conditions, we examined participants while walking barefoot and in their regular shoes. Making use of body-worn sensor technology, we were also able to examine potential gait alterations over two distances: 1) a short walkway that more closely represents an individual’s home environment and 2) a long walkway that more closely represents an individual’s walking environment outside of the home.

Methods

This study received ethical approval from the institutional review board at Rosalind Franklin University (North Chicago, Illinois). All of the participants received oral and written information and signed informed consent forms before participating.

Participants

Patients with DPN were included if they were older than 18 years and were diagnosed as having diabetes for at least 5 years and as having DPN for at least 3 years as determined by vibratory perception threshold (VPT) testing and monofilament testing. The VPT test was conducted at the tip of the great toe, and DPN was determined if the VPT was greater than 25 V. Patients were excluded if they had an active foot ulcer, had orthopedic or surgical problems influencing gait (eg, Charcot’s arthropathy or amputation), were unable to walk without a walking aid, or had a documented history of non–diabetes-related peripheral neuropathy or other neurologic abnormalities influencing gait.

Nondiabetic participants were recruited from the same outpatient clinics. Individuals in this control group had a normal VPT of less than 25 V and had to be able to walk for at least 10 min without a walking aid. Individuals with visual disturbance or with a documented history of neurologic, orthopedic, or surgical conditions thought to influence gait were ineligible. Attempts were made to match the control group to the DPN group by age (±10 years), sex, and body mass index (BMI). Based on our previous work, the average BMI (calculated as weight in kilograms divided by height in meters squared) in the DPN group was 32.65, so we accepted up to a 15% difference in matching BMI.

Materials

Participant gait was evaluated using a validated gait analyzer system (LEGSys BioSensics LLC, Cambridge, Massachusetts) (Fig. 1) with five wearable sensors attached to the right and left anterior shins, the right and left anterior thighs, and
posteriorly to the lower back. Each sensor measures the angular velocity of the segment in the sagittal plane (flexion-extension). A triaxial gyroscope and triaxial accelerometer sensor module was attached to the lower back. This sensor module measured center-of-mass motion during walking. The method for calculating spatiotemporal parameters of gait and its validity has been previously described in detail.\textsuperscript{12,32} Based on statistical intercycle fluctuation of gait velocity, the beginning of gait steady state was objectively identified as described in previous publications.\textsuperscript{25,40} In summary, the SD of the velocity of six successive strides (three right and three left strides) was calculated from the first stride on (eg, the SD of strides 1, 2, 3, 4, 5, and 6; 2, 3, 4, 5, 6, and 7; ...). The marker of the beginning of steady state walking was the first stride of the group of six strides with an SD below the median SD of all the analyzed strides \pm 6\% related to the sensitivity of the sensors.\textsuperscript{32}

The LEGSys device can extract more than 30 different spatiotemporal parameters of gait. For the purposes of this study, we focused on nine gait parameters hypothesized to be the most important for the risk of falling:\textsuperscript{3,41,42} 1) gait initiation velocity, 2) average stride velocity during steady state walking, 3) coefficient of variation of stride velocity during gait steady state phase (gait steadiness), 4) average range of motion of center of mass during each stride in the mediolateral direction, 5) average range of motion of center of mass during each stride in the anteroposterior direction, 6) average double support phase as a percentage of stride time, 7) average stride time, 8) average stride length, and 9) number of steps required to achieve gait steady state. The coefficient of variation of stride velocity was defined as the SD of measured stride velocities during steady state divided by the average of stride velocities multiplied by 100.

**Procedure**

Participants underwent a standard pretesting clinical examination that included a random capillary blood sugar test. After placement of the body-worn sensors, participants were asked to walk at their habitual speed for a short distance (22 ft [\(\sim 7\text{ m}\)]) and a long distance (66 ft [\(\sim 20\text{ m}\)]) under two footwear conditions: barefoot and regular shoes. The testing order was randomized. Each trial was performed twice, with the first trial serving as a warm-up. Only data from the second test were included in the final analysis. At the end of each trial, participants were asked to rest briefly to avoid fatigue before starting the next test.

**Statistical Analysis**

This study examined three main hypotheses: 1) gait deteriorates in patients with DPN, 2) gait alterations in patients with DPN are more pronounced over longer walking distances (ie, 66 ft) compared with shorter walking distances (ie, 22 ft), and 3) footwear can remedy gait alterations seen in patients with DPN. Comparisons between the healthy and DPN groups across different walking conditions were made using one-way analysis of variance (ANOVA) and the Scheffe post hoc test. Repeated-measures ANOVA was used to test for differences in the gait parameters between the long and short walking distances and between the barefoot and shod conditions. In cases where the data were found to be nonspherical, a Huynh-Feldt adjustment was used to determine significance. When a significant difference (\(P < .05\)) was found, the least significance difference test was used as the post hoc to assess pairwise comparisons. In addition, ANOVA was used to examine whether small differences in matched variables (eg, age,
BMI, and sex) occurred between the DPN and control groups. The Pearson correlation coefficient (r value) was used to examine the correlation between the continuous gait parameters, BMI and VPT. Results are expressed as mean ± SD. A $P \leq .05$ was considered statistically significant. All of the statistical analyses were performed using a commercially available software program (SPSS, version 19; SPSS Inc, Chicago, Illinois).

**Results**

**Participant Characteristics**

Table 1 summarizes the characteristics of the participants. Overall, 12 patients with DPN (eight men and four women with the following mean ± SD values: age, 60 ± 12 years; BMI, 33.2 ± 6.4; duration of recognized diabetes, 10 ± 13 years; and duration of recognized DPN, 6 ± 4 years) were recruited for this study. Individuals in the control group were matched on age ± 10 years and BMI ± 15% with recruited patients with DPN. Eight individuals in the control group were recruited (five men and three women with the following mean ± SD values: age, 60 ± 6 years; BMI, 27 ± 3.2). No significant difference was observed for age ($P = .85, 95\%$ confidence interval $[CI] = -8.8$ to 10.6 years) and height ($P = .70, 95\%$ CI $= -12.8$ to 8.9 cm) between patients with DPN and individuals in the control group. However, BMI of patients with DPN was significantly higher than that of individuals in the control group ($P < .05, 95\%$ CI $= 1.1$ to 11 kg/m$^2$). All of the patients with DPN had a VPT of 26 V or higher, and all of the individuals in the control group had a VPT of 22 V or lower.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Patients with DPN (n = 12)</th>
<th>Participants in Control Group (n = 8)</th>
<th>$P$ Value</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male sex (%)</td>
<td>66</td>
<td>75</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Age (years)</td>
<td>60 ± 12</td>
<td>60 ± 6</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>175 ± 11</td>
<td>177 ± 12</td>
<td>.7</td>
<td>-13 to 9</td>
</tr>
<tr>
<td>BMI</td>
<td>33.2 ± 6.4</td>
<td>27.0 ± 3.2</td>
<td>.02</td>
<td>1.1 to 11.4</td>
</tr>
<tr>
<td>VPT, right foot (V)</td>
<td>56 ± 25</td>
<td>19 ± 4</td>
<td>&lt;.001</td>
<td>18 to 55</td>
</tr>
<tr>
<td>VPT, left foot (V)</td>
<td>61 ± 29</td>
<td>20 ± 3</td>
<td>&lt;.001</td>
<td>19 to 63</td>
</tr>
<tr>
<td>Duration of DM (years)</td>
<td>10 ± 13</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Duration of DPN (years)</td>
<td>6 ± 4</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Note: All measurements are presented as mean ± SD except where indicated otherwise.

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); CI, confidence interval; DM, diabetes mellitus; DPN, diabetic peripheral neuropathy; NA, not applicable; VPT, vibration perception threshold.

**Gait Alterations in the DPN Group**

Table 2 summarizes the comparison between patients with DPN and individuals in the control group. Most gait parameters showed alterations in patients with DPN during the barefoot and shod conditions compared with those in the control group. However, the effect size was usually larger in the long walking distance trials, and none of the observed differences were statistically significant in the short walking distance trials.

In the long walking distance trials, gait speed during the gait initiation and gait steady state phases was reduced on average by 15% (Fig. 2A). This reduction, however, was not significant ($P = .09, 95\%$ CI $= -0.35$ to 0.04 m/sec). During the long walking distance trials, gait intercycle variability (gait unsteadiness) defined by coefficient of variation of gait velocity$^{11,12}$ was 84% higher in the DPN group ($P = .01; 95\%$ CI $= 0.1$ to 3.7%) while walking barefoot (Fig. 2B). Wearing shoes significantly reduced the intercycle variability in patients with DPN by 46% ($P = .02, 95\%$ CI $= -3.4$ to $-0.27$), and intercycle variability was not significantly different between the groups during the shod condition. Similarly, double support time was more than 20% during the barefoot and shod conditions in those with DPN ($P = .03, 95\%$ CI $= 0.34$ to 10%) (Fig. 2C). There were no significant differences in range of motion of center of mass for the anteroposterior and mediolateral directions ($P > .2$). There also was no observed correlation between BMI and coefficient of variation of gait velocity ($r = -0.23, P = .5$) or between BMI and double support duration ($r = 0.06, P = .84$).

We observed a relatively high correlation between intercycle variability and VPT values during the long walking distance and barefoot condition in
patients with DPN ($r = 0.77, P < .001$). Decreased vibratory perception, and, therefore, higher VPT values, was positively associated with increasing intercycle variability. Also, a moderate correlation was found between VPT values and double support time during the barefoot condition in the DPN group ($r = 0.50, P = .03$), suggesting that poorer somatosensory feedback increases the requirement for longer periods of double support. These correlations between VPT levels and intercycle variability and double support time, however, no longer remained during the shod condition. Finally, no correlations were found between VPT and intercycle variability or VPT and double support time in the control group over any of the conditions.

The results suggest that individuals in the control group required a mean ± SD of $3.4 ± 1.7$ steps to reach gait steady state during the shod condition (Table 2). Although, patients with DPN required slightly more steps to reach gait steady state (mean ± SD: $4.2 ± 1.9$ steps), the difference was not significant ($P > .05$). Similar results were observed during the barefoot conditions. The intercycle variability was significantly higher during gait initiation in the DPN group compared with the steady state phase ($4.83\%$ during gait initiation versus $4.04\%$ during gait steady state; $P = .03$, 95% confidence interval).

### Table 2. Spatiotemporal Parameters of Gait for Patients with DPN and Participants in the Control Group

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Patients with DPN</th>
<th>Participants in Control Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short Walking Distance</td>
<td>Long Walking Distance</td>
</tr>
<tr>
<td></td>
<td>Barefoot</td>
<td>Shod</td>
</tr>
<tr>
<td>Gait initiation velocity (m/sec)</td>
<td>0.81 ± 0.28</td>
<td>0.85 ± 0.24</td>
</tr>
<tr>
<td>Stride velocity (m/sec)</td>
<td>0.82 ± 0.27</td>
<td>0.85 ± 0.24</td>
</tr>
<tr>
<td>CV (stride velocity) (%)</td>
<td>4.1 ± 2.5</td>
<td>4.2 ± 4.0</td>
</tr>
<tr>
<td>COM_ML</td>
<td>4.3 ± 3.3</td>
<td>4.7 ± 2.3</td>
</tr>
<tr>
<td>COM_AP</td>
<td>4.5 ± 1.9</td>
<td>5.1 ± 1.6</td>
</tr>
<tr>
<td>Double support duration (%)</td>
<td>25.2 ± 8.4</td>
<td>25.1 ± 6.5</td>
</tr>
<tr>
<td>Stride time (sec)</td>
<td>1.16 ± 0.19</td>
<td>1.20 ± 0.16</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>0.92 ± 0.22</td>
<td>0.99 ± 0.20</td>
</tr>
<tr>
<td>No. of steps</td>
<td>2.5 ± 1.3</td>
<td>2.2 ± 0.7</td>
</tr>
</tbody>
</table>

Note: All measurements are presented as mean ± SD. Boldface values indicate statistical significance.

Abbreviations: COM_AP, center of mass during each stride in the anteroposterior direction; COM_ML, center of mass during each stride in the mediolateral direction; CV, coefficient of variation; DPN, diabetic peripheral neuropathy.
CI = 0.1% to 1.6%). No statistically significant difference was observed in the control group between gait initiation and gait steady state.

The Impact of Footwear

The benefit of footwear was significant only during the long walking distance trials. During these trials, wearing shoes significantly improved gait initiation velocity (P < .005, 95% CI = 0.034 to 0.08 m/sec) and gait steady state velocity (P < .01, 95% CI = 0.03 to 0.08 m/sec). Independent of age, BMI, and sex, the number of steps required to achieve steady state was reduced by wearing shoes (P = .05). As indicated previously herein, the benefit of footwear in improving intercycle variability was also significant in the DPN group during the long walking distance condition.

The Impact of Walking Distance

Most gait parameters were significantly different between the short and long walking distance trials for both groups and irrespective of footwear condition. By increasing walking distance, gait velocity during gait initiation and steady state was significantly increased (P < .001, 95% CI = 0.04 to 0.1 m/sec), and intercycle variability was significantly reduced (P < .001, 95% CI = −4% to 1%). On the same note, increasing the walking distance reduced double support time (P = .02, 95% CI = −1.7% to −0.1%), increased stride length (P = .001, 95% CI = 1.8 to 6.1 cm), and increased the number of steps required to achieve steady state (P < 10⁻⁵, 95% CI = 0.8 to 2.3 steps). The impact of the footwear condition on intercycle variability was apparent only when going from short to long walking distance (P < .05).

Discussion

This study explored potential gait alteration due to DPN during shod and barefoot conditions and at short and long walking distances. The testing protocols were designed to mimic indoor and outdoor conditions, where participants walked over short and long distances with and without shoes. The chosen short walking distance (~7 m) is comparable with the walkway usually used for gait analysis inside of a standard gait laboratory. The results suggest that patients with DPN experienced gait deterioration in all of the predefined outcomes. However, the deterioration was significant only for gait unsteadiness and double support duration for the long walking distance trials. Increased gait unsteadiness experienced by patients with DPN may suggest impaired automaticity of gait possibly by altered somatosensory feedback. Gait alterations of patients with DPN were more pronounced while walking barefoot, suggesting that there may be a benefit to wearing shoes. Shoes may help improve gait automaticity by enhancing somatosensory feedback via shoe contact with sensate skin at the ankle, by increasing the overall contact area, or by the added extra weight of the shoe.

Changes in stiffness may also explain some of the observed effects in patients with DPN while wearing shoes. Runners are known to change leg stiffness in response to barefoot and shoe running. Although stiffness of the shoe and forefoot are synergistic, it is dominated by the foot. In patients with DPN, who have limited joint mobility and decreased stiffness, shoes may contribute more synergistically to stiffness, thus enhancing the magnitude of the somatosensory afferent stimulus.

Although gait deterioration due to DPN was also observed during short walking, the effect size was lower. Decreased number of strides may influence the stability of the mean and coefficient of variation estimates. Similarly, the high gait variability with DPN would require a higher number of strides to provide a more stable estimation of mean values. This observation suggests that typical clinical assessment of gait over a few steps (eg, the gait laboratory or clinic condition) may not detect clinically significant deterioration in patients with DPN.

Previous studies have demonstrated that increased gait unsteadiness and double support duration are associated with increased fall risk in older adults. Indeed, in a randomized trial studying customized footwear in diabetic patients with previous foot ulcer, 54% of patients reported a fall in the first year, representing a much higher rate than previously reported in similarly aged populations. Patients wearing the customized footwear had a significant reduction in fracture risk.

Customized footwear may increase feedback from cutaneous receptors in the foot and ankle in patients with DPN, thus improving balance and gait stability during walking. Previous work also suggests that wearing customized foot orthoses may reduce gait unsteadiness. Future studies should examine whether customized foot orthoses may reduce gait variability in DPN patients who have high gait unsteadiness.
To our knowledge, this study is the first to explore gait initiation in DPN. In particular, gait initiation is a crucial phase in DPN owing to relatively high shear forces during this phase. In other words, the most dangerous period for a moving body is during gait initiation and termination because this is when the body is most subject to accelerating and decelerating forces. This is analogous to an airplane during takeoff and landing. The greatest risk for a crash is during takeoff and landing, during which the plane must endure significant stress from the extreme accelerations and decelerations. Just as a plane reaches a steady state at its cruising altitude, people achieve a steady state walking. Individuals with DPN take a particularly long time and distance to reach a smooth walking gait. These results suggest that gait unsteadiness in the DPN group is significantly higher during gait initiation than during steady state. In addition, it takes more than four steps (during the shod condition) for a diabetic patient with neuropathy to reach steady state, which was 24% higher than the control group and approached significance ($P = .12$). Although four steps seems trivial, when we look at it in the context of overall daily activity it becomes very important. Najafi et al.$^{52}$ revealed that patients with DPN initiated more than 350 episodes of walking per day. Furthermore, these episodes are often short (<20 steps), which amplifies the importance of, and potential risks associated with, gait initiation during activities of daily living. With new work$^{25}$ suggesting that gait initiation times can be altered depending on the type of orthoses worn, future studies should address varying combinations of footwear and orthoses to see if these reduce gait initiation and gait unsteadiness, two important parameters that may contribute to foot ulceration and risk of falling in DPN.

There are limitations to this study. We may have been underpowered to detect differences in the other gait parameters. Further study with a larger sample size is required to address other gait alterations associated with neuropathy complications. Also, despite attempted matching for BMI, the DPN group had a significantly higher mean BMI than the control group. However, in the univariate analysis, we did not observe a significant association between BMI and gait unsteadiness or double support time, indicating that the observed gait deterioration in patients with DPN was independent of BMI.

Conclusions

This study examined spatiotemporal parameters of gait in patients with DPN and in an age-matched control group. We demonstrated that those with DPN had greater gait unsteadiness and required longer double support times, particularly while walking barefoot. The amount of gait unsteadiness was highly correlated with worsening vibratory perception in the DPN group. Wearing shoes, however, improved gait steadiness. Finally, this study suggests that gait alterations associated with DPN should be carefully assessed over ample walking distances (preferably $>$20 m). Future studies should confirm the observed results in a larger sample. Also, the proposed parameters should be further explored using differing customized footwear/orthoses combinations to determine their influence on gait initiation and unsteadiness.

Financial Disclosure: This study was supported by an American Podiatric Medical Students’ Association award.

Conflict of Interest: None reported.

References